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NASA Unmanned Flight Anomaly Report:

INVESTIGATION OF THERMAL SENSOR FAILURES ABOARD UNMANNED SPACECRAFT

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FOREWORD

This Reliability Interim Significant Report (RISR) document was prepared by the Reliability Engineering Section of the Jet Propulsion Laboratory's Office of Engineering and Review, Systems Assurance Division, to describe recent significant results and progress of technology tasks sponsored by NASA's Office of Safety and Mission Assurance (Code Q). Issues discussed herein provide new or recently concluded programmatic information which can be implemented to better apply the Reliability disciplines to hardware, thereby increasing efficiency and effectiveness. Prudent application of this information moves the reliability disciplines toward faster, better, cheaper test and analysis efforts. Questions regarding this report should be directed to the author or to the Manager of the JPL Reliability Engineering Section.

PREFACE

The NASA Unmanned Flight Anomaly Reports present the results of a series of analyses of in-flight hardware anomalies which have occurred on Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), and U.S. Air Force unmanned space programs. All on these analyses are funded by NASA Code QT under Research Technology Operation Plan (RTOP) 623-63-03, entitled *Flight Anomaly Characterization*. The objective of these analyses is to search for meaningful characterizations of in-flight anomaly data relating to trends, patterns, or similarities that can be exploited to improve Product Assurance Program processes, ultimately leading to reduced numbers of anomalies on future unmanned flight programs.

For further information on the content of this report, contact David Oberhettinger at (818) 542-6960. For additional copies of this document, contact the JPL Document Vellum Files at extension 4-5004.

ABSTRACT

This NASA Unmanned Flight Anomaly Report analyzes in-flight anomalies related to defective thermal sensor assemblies on Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), and U.S. Air Force unmanned space programs. Thermal sensor telemetry data aid Mission Operations in monitoring spacecraft health and diagnosing in-flight problems. The objective of the analysis was to:

1. Determine whether the anomalies were isolated incidents or whether the failure modes represent a risk to future unmanned missions.

2. Identify product assurance process improvements to reduce mission risk.

The report identifies a pattern of hardware failures due to inadequate allowances for strain relief and environmental conditions. The impact of these failures on the respective missions was rated as minor, but the failures reduced the ability of ground controllers to detect potentially serious temperature changes in unmanned spacecraft. The report recommends (1) flight qualification of thermal sensor hardware and (2) development of a standardized sensor mounting configuration(s).

REFERENCE: (1) *Development of a Method for Flight Anomaly Characterization*, JPL document D-11382, dated January 1994.

I. INTRODUCTION

Scope

This NASA Unmanned Flight Anomaly Report presents the findings of an analysis of in-flight anomalies in which loss of thermal sensor data occurred. The investigation is limited to the JPL Viking, Voyager, Magellan, and Galileo missions, and to those Goddard Space Flight Center (GSFC) and U.S. Air Force unmanned missions documented in the JPL Payload Flight Anomaly Database (PFAD).

This report is one product of the Flight Anomaly Characterization (FAC) study, funded under NASA RTOP 323-63-02. The methodology established in Reference (1) was applied to the analysis of thermal sensor failures.

Purpose

This study is one of a series of Unmanned Flight Anomaly Reports funded by NASA Code QT to document conclusions drawn from investigations of in-flight spacecraft and instrument anomaly data. The results are principally directed toward recommending product assurance process improvements which would lead to a reduced level of risk for future unmanned space missions. The conclusions from these studies may assist in managing the risks inherent in the "faster-better-cheaper" design philosophy.

Method

Reference (1) suggests a two-step methodology for grouping and analyzing sets of in-flight spacecraft anomalies with common characteristics, allowing identification of product assurance implications for future programs. In that document, a flow diagram was prepared showing pertinent data from each in-flight anomaly report in the PFAD. (To date, this diagram has been prepared only for the major JPL spacecraft due to the large number of GSFC and USAF programs.) After the anomalies were arranged by spacecraft and subassembly, those that appeared related were designated as a group for further analysis. A second flow diagram (see Figure 1) is prepared for each candidate grouping of anomalies with possible product assurance program significance; thermal sensor (TS) failures were identified as one of these groupings. This second diagram is further analyzed to validate the suspected correlations (identified by "cross-links" in Figure 1), and to identify any product assurance program implications.

II. DATA ANALYSIS

JPL Programs

Applying the flow diagram technique to major JPL spacecraft programs, one characteristic pattern that emerged was a number of mid-mission TS failures. In-flight TS instrument anomalies were not included because of the great variation of reliability practices applied to instrument design. The JPL failures are examined in Figure 1 using the flight anomaly characterization methodology demonstrated in Reference (1). Fourteen in-flight TS anomalies rated as "Minor/No Impact" on the mission were documented on the Voyager 1, Magellan, and Galileo flight programs. The majority of these TS failures were aboard Galileo-- specifically on the thrusters and the radioisotope thermoelectric generator.

The mission impact of the JPL anomalies was not rated as significant due to redundancy and because diagnostic monitor failures have no direct impact on performance of the spacecraft mission. It is still early in the Galileo mission, and more sensing points may yet be lost. Although system reliability is not directly compromised, an impact on JPL mission operations may result from an inability to detect unacceptably high temperatures. For example, the temperature sensors attached to the RTG case provided useful diagnostic information on temperature-induced power output fluctuations anticipated as the spacecraft neared the sun. Also, "hot operation" of the thrusters could cause a runaway condition and subsequent catastrophic engine failure. In unmanned spacecraft, data from temperature sensors are a key to real-time characterization of operating conditions so that corrective action can be taken before serious damage results. When engine overheating was detected during the Galileo mission, for example, the problem was alleviated when mission controllers switched the thrusters to pulse mode.

Voyager TS Anomalies. As indicated in Table 1, a single TS anomaly was documented on Voyager 1. The sensor was located on a waveguide behind the high gain antenna; telemetry gave an indication of X-band feed saturation. The indication was judged to be erroneous and attributable to a TS failure, and the data from the failed sensor were ignored. The thermal sensor failed three years into the mission.

Figure 1

Investigation of Thermal Sensor Failures - JPL Database

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Table 1 - Thermal Sensor Failures on JPL Flight Programs

Characterization	No. of Anomalies	Mission Impact	JPL Program	Conclusion	Product Assurance Program Implications
Apparent random failure of one sensor.	1	Minor/None	Voyager 1	Possible bad part. Inconclusive.	None. Single failure occurred 3 years into the mission.
Failed sensors had been subjected to environmental stress, especially thermal stress.	5 8	Minor/None Minor/None	Magellan Galileo	Thermal sensors demonstrate vulnerability to high temperature and to temperature cycling.	1. Stress relief is needed for thermal sensors subject to temperature cycling. 2. Fully define environmental requirements for part selection. 3. Perform mock-up tests of the flight configuration, and cycle to failure to establish temperature margins.

Magellan TS Anomalies. Five Magellan TS failures were documented on a single PFR (PFR No. 52244). These temperature sensors failed in various locations at various times starting approximately 1-1/2 years after launch:

Part No.	ISA No.	Anomaly Date	Location	Symptom
E-0014	9053	90-295	Multi Layer Insulation T2	Erratic Performance (SADM)
E-0100	9054	90-296	HGA Reflector Sensor	Erratic Performance (SADM)
E-0015	8766	90-336	Multi Layer Insulation T3	Failed High (255dN)
E-0106	8761	91-078	Medium Gain Antenna	Failed High (255dN)
E-0184	9280	91-218	Shunt Radiator T1	Erratic Performance

Three of the sensors began giving erratic readings (two of which were correlated with solar array drive vibration) and the other two read full scale, indicating an open circuit. Sensor E-0100, listed above as exhibiting erratic performance, also failed later as an apparent open circuit. Prior to the failure of Medium Gain Antenna sensor E-0106 during orbit 1733, it was cycling approximately 155^0C per orbit and had been performing erratically. HGA reflector sensor E-0100 was also analyzed: it began to exhibit erratic performance 17 months into the mission after experiencing both extreme temperature cycling of 100-150^0C and solar array drive motor (SADM) vibration. No details are available on the environment of the other three anomalies.

Galileo TS Anomalies. Of the eight Galileo failures, one occurred in the Near Infrared Mapping Spectrometer (NIMS) instrument, three in the Electrical/Power Subsystem (in the RTG), and four in the Propulsion Subsystem. The single NIMS failure three years after launch appears to be a random failure. The data on the four engine sensor failures must be weighed in view of the fact that the twelve temperature sensors on the 10-N thruster chambers were never flight qualified. The German thruster manufacturer, MBB, installed the sensors at the last minute, potting each sensor with a ceramic-filled epoxy into a stainless steel cup welded to the chamber. The Galileo project office had intended to eliminate the sensors as unneeded due to a change to a cooler "pulse mode" of engine operation, but MBB left the parts in place.

Drawings show that the three resistance thermal devices (RTDs) that failed in the RTG were from a set of four, spaced evenly around the circumference of the active cooling system (ACS) interface plane. JPL confirmed with General Electric that loss of the temperature sensors would not affect

RTG function, and so the failures were rated as presenting no mission impact. The failures were isolated to the transducers and directly associated hardware: false indications from Command Data Subsystem (CDS) hardware or software would have resulted in a more random anomaly distribution. Although the above arguments favor a defective part, the cognizant component engineer reports that the Rosemount RTDs are widely used in other applications and have experienced no significant industry failures.

The failure mode for all the Galileo temperature sensors is an apparent open circuit, which results in telemetry indicating a full scale temperature reading. The Rosemount sensor used in the RTG is a Model 175BM (pure platinum wire with a platinum alloy sheath), purchased and installed by General Electric; the thrusters used a Model 118AKT (pure platinum wire with a ceramic coating), a model purchased and used by JPL for 25 years. The Model 118 drawing is included as Attachment A.

The common factor between the three Galileo TS failures in the RTG and the four in the hot thrusters is sensor location in a high temperature area exceeding 150^0C. Of the other 50 or more sensors in the Galileo spacecraft, none are known to experience temperatures greater than 150^0C. However, the 175BMs in the RTG and the 118AKTs in the thrusters are rated to 370^0C and 400^0C, respectively. JPL looked at solder joint thermal cycle fatigue-- the RTG is subject to constant high temperatures while the thrusters experience both high temperatures and deep cycles-- but the timing of the failures is not consistent with this hypothesis. Part failure is not a likely cause because the RTD vendors perform thermal cycling during acceptance test; Rosemount reportedly thermally shocks every part. The high level of Galileo inheritance (including the CDS and RTG) argues against a hypothesis of problems with associated equipment.

If Galileo RTDs or their mounts are vulnerable to thermal cycling, the engine chamber would seem the most likely environment to cause failures. This is because the thruster temperature near the sensor rises from 10^0 to 160^0C in less than 2 minutes at the start of a burn. Over a 90 minute period, the Galileo thrusters were fired 162 times to permit a fly-by of the asteroid Gaspra. During vendor acceptance test, the Model 118AKT is ramped only 10 times to 105^0C.[1] Also, this piece part has never been qualification tested by JPL.

In a study of the 10-N thruster failures, J. M. Weiss (JPL Section 353) concluded that the most likely failure mechanism is either a fracture of the sensing wire (0.0006 inch diameter) within the sensor or the fracture of a lead wire (0.012 inch diameter), resulting in an open circuit and causing a telemetry channel to display the 255dN maximum value.[2] Unlike the Model 175BM enclosed in a solid stainless steel case, the 118AKT is a fragile piecepart with a butt welded connection to the gold-plated copper lead wires. The failure analysis attributes the fracture to differences in the rate of expansion of the wire and the sensor body. The telemetry was consistent with a sudden separation of the wire at the beginning of the burn, followed by erratic readings during the cool down period when the fractured wire may have slowly regained contact.

Both the Magellan and Galileo TS failures appear temperature related. In such environments,

[1] W.H. Tyler presentation of April 27, 1990, page 9.

[2] J.M. Weiss IOM 353GLL-91-004 of 12/28/90

providing for adequate stress relief in the weld between the sensor and lead wires is one measure to prevent recurrence on future missions. Figures 3 and 4 **(Figures 3 and 4 are not compatible with this format)** plot the occurrence of the RTG and thruster sensor failures. While the data are too limited to be conclusive, the failure curves are not inconsistent with component wearout due to lack of stress relief. However, aside from any potential impacts on mission operations, the Galileo failure analysis concluded that expensive hardware tests to identify the failure mechanism may not be justifiable from a spacecraft reliability standpoint. Still, when the JPL data is coupled with the following non-JPL anomaly data, they support the need for some limited testing of mounting arrangements, lot sampling, and flight qualification for future builds.

GSFC Programs

Flight histories of non-JPL spacecraft were also reviewed to assess the overall extent of TS vulnerabilities. Of the Goddard Space Flight Center in-flight anomaly reports contained in the PFAD database, six document TS failures. These six were written on 22 discrete parts, as indicated in Table 2.

Table 2 - Thermal Sensor Failures on GSFC Flight Programs

Characterization	No. of Anomalies	Mission Impact	GSFC Program	Conclusion	Product Assurance Program Implications
Failure of 17 solid state sensors located on the outer areas of the spacecraft. (1 PFR)	17	Minor/None	AMPTE-CCE	Suspect part damage from ionizing cosmic radiation.	Improve peer review of parts selection to match the expected radiation dose.
Sensors on solar array panels 1,2,3 & 4 render anomalous temperature readings on a diurnal cycle. (4 PFRs)	4	Minor/None	LANDSAT 4	Failure of flat ribbon cable connectors due to expansion of connector potting material when heated.	Perform mock-up tests of the flight configuration and do temperature cycling to failure to establish margins.
Anomalous temperature readings from a single sensor. (1 PFR)	1	Minor/None	TIROS N	Random part failure.	None: other temp. sensors are nominal.

On each of four LANDSAT 4 solar panels, the thermal sensor failed with a full scale temperature reading; the reading returned to normal at the spacecraft "night" and failed again whenever the temperature rose above 10^0C. The LANDSAT 4 anomalies were attributed by GSFC to failure of flat ribbon conductors due to the large coefficient of expansion of the connector potting material when exposed to orbital temperature cycles. Recommendations for LANDSAT D included use of round wires, crimped insert pins, stress relief, and harness cable clamp supports. Hence, Goddard's findings are also consistent with part damage from thermal cycling. The 17 AMPTE-CCE failures show solid state sensor vulnerability to radiation as an environmental stress factor. The Galileo, LANDSAT 4, and AMPTE-CCE (and possibly the Magellan) TS failures could all potentially have been prevented by application of the product assurance measures recommended in Tables 1 and 2.

ODAP (USAF) Database

The JPL PFAD database contains flight anomaly data from the U.S. Air Force Orbital Data Acquisition Program (ODAP); PFAD presently holds 1871 anomaly records on 14 USAF spacecraft. These spacecraft are not identified by name nor mission, but by two sets of sequential numbers-- one set for classified programs and one for unclassified. The purpose of accessing ODAP was to determine whether the USAF data corroborated the TS failure trends identified in Figure 1. ODAP was found unsuited to more detailed analysis because certain data (such as vendor identification) have been expunged from the ODAP database copy provided to JPL, and USAF memos and other failure analysis documentation is unavailable.

Due to the large number of reports, it was necessary to search ODAP by key words to identify TS anomalies. Searches were performed on the words "sensor," "thermistor," and "transducer." Each report elicited by the search was reviewed for valid TS failures, resulting in 186 reports documenting 235 TS anomalies (some reports documented multiple anomalies) on 7 unnamed USAF spacecraft.

Table 3 provides a characterization of the USAF anomalies. Some of the listed anomaly categories may appear to have elements in common, but an effort was made to retain the substance of the original USAF analysis.

Table 3 shows that environmental factors, especially thermal cycling, apparently have a major impact on ODAP TS failures. We see the same lead breakage, bonding compound expansion and contraction, electrical connections which vary with diurnal temperature cycles, and other unattributed RTD failures. Anomalies where a thermally induced failure mechanism is unlikely is represented in Table 3 by a dash in the right column-- these account for only 34 percent of the total anomalies in Table 3.

Table 3 also identifies electrostatic discharge (ESD) as an additional environmentally induced failure mode for U.S. Air Force thermal sensors. However, ODAP provides incomplete information on the failed component.

Table 3 - Thermal Sensor Failures on USAF Flight Programs

Anomaly Characterization	No. of Anomalies	Likely Thermal Induced
Sensor device failure. Results in loss of temperature measurement datum. The cause is undetermined.	92	some
Sensor device failure. Results in diurnal cycling to an open circuit (reads full scale). Caused by debonding, lead failure, or poor electrical connection.	11	11
Sensor device failure. The thermal environment of the sensor location suggests failure due to a temperature sensitive element or the use of bonding compound.	14	14
Temperature readings show a constant measurement offset error. Caused by sensor device debonding.	5	5
Sensor device short circuit. Probably caused by epoxy bond shifting due to thermal contraction. Longer pigtails were recommended to negate the need for splicing.	2	2
Sensor device short circuit caused by insufficient insulation or a ground loop isolation problem.	7	-
Sensor device failure. Caused by capacitor failure due to electrostatic discharge.	22	-
Sensor device failure. Likely caused by electrostatic discharge.	11	-
Temperature monitoring circuit fails open (reads full scale). The cause is undetermined. Nominal readings resumed in 5 instances.	24	24
Failure of a sensor device or the temperature monitoring circuit: not an open nor a short. The cause is undetermined.	6	-
Temperature monitor gives intermittent readings on a daily or diurnal cycle. The cause is undetermined.	3	3
Temperature monitor readings are slightly (10^0C) too low, or give a one-time low signal. Caused by a poor electrical connection in the temperature monitoring circuit.	5	5
Temperature readings are 40^oC too low. Caused by low voltage output from the temperature sensor amplifier.	2	-
Occasional random signal, or the monitor reads open. Caused by a loose Jiffey connector in the cabling.	22	-
Other monitor circuit or device failures. Caused by a workmanship error or the cause is unclear.	9	-
Total ODAP Thermal Sensor Anomalies:	235	64*

*Some of the 92 sensor failures in the first row are likely to have been thermally induced, but it has not been substantiated.

The ODAP anomalies are not included in Figure 1 due to the lack of detailed information on the hardware and the mission. From the data, though, it is clear that the spacecraft carry navigation and military sensor payloads. Figure 5 shows the distribution of the 235 TS anomalies among subsystems aboard the 7 spacecraft. About one-half of the USAF anomalies occurred in Telemetry, Tracking and Command, and the balance are mostly payload related.

III. CONCLUSIONS

This study has identified groups of in-flight anomalies where thermal sensors were affected by thermal dwell, temperature cycling, electrostatic discharge, or radiation. NASA and military flight experience supports the need to assure adequate environmental margins in the design of TS installations, with special attention to stress relief in sensor applications subjected to thermal cycling. All of the NASA anomalies studied were rated as having had a minor mission impact. The Galileo spacecraft presently retains thermal sensing capability: one sensor in the ring of four on the RTG ACS remains functional, and 10-N thruster temperature is known so long as the sensors on the nearby cluster thrusters remain intact. However, the mission is not yet over, and the thermal sensors that have proven to be most vulnerable are also those where temperature monitoring is most critical.

The Rosemount Model 118 series of platinum resistance temperature sensors has been used on JPL spacecraft since the 1960s, and it remains a commonly used sensor series. Due to this inheritance, JPL has never flight qualified any sensor in this series nor any Model 118 mounting process. The evidence presented in this report points to design of the sensor mount as the probable cause of most failures; no trend of bad piece parts were found in either the NASA or military missions examined. Although a typical JPL spacecraft contains hundreds of thermal sensors, most subsystems on JPL spacecraft have completed their mission without experiencing a single reported TS anomaly. However, it is clear that special design considerations apply to qualifying a sensor mounting process suitable to high stress applications.

Ground failures have been documented in Viking and other JPL programs. The sensitivity of thermal sensors to environmental conditions, adhesive failure, and handling damage demonstrates the need for improved design specifications. Little progress has been made in understanding the major failure mechanisms in TS application; and thermal sensor vulnerability remains a concern on current JPL programs.

IV. RECOMMENDATIONS

Thermal sensors are often installed on critical spacecraft subsystems for which no redundant backup exists, such as major structural components, solar arrays, and RTGs. In unmanned spacecraft, data from diagnostic monitors are a key to real-time characterization of hardware operating conditions and pinpointing of in-flight problems. These data provide mission operations personnel with clues to hardware degradation or to corrective action strategies.

The findings of this study support the need for additional product assurance and environmental engineering measures in the design of these important spacecraft health data sources. The following recommendations are provided for the design of TS assemblies on future spacecraft and instruments:

1. Study TS temperature cycling to derive engineering guidelines for stress relief commensurate with the mission and the anticipated environment. Where the mission profile compels screening out potential in-flight failures, perform further analysis on the advantages and disadvantages of thermal cycling the temperature sensors on the ground.

2. Develop a standard mounting configuration(s) and engineering procedure for RTDs. Conduct mock-up tests of the flight configuration in high temperature and thermal cycle environments. Based on the test data, flight qualify the piece part and assembly procedure, and determine environmental margins based on test-to-failure. The qualified assembly procedure should be applicable to a wide range of spacecraft sensor locations and environments.

3. Review the established engineering specifications and procedures on the use of bonding and potting compounds, including evaluation of adhesive durability and the effects of environmental stress. Develop improved guidelines if necessary.

4. The component engineer's cognizance typically ends with the receipt of acceptable piece parts, permitting the design engineer to accept the sensor without fully understanding the limitations on its application. Institute enhanced peer review of design applications, and implement product assurance measures to ensure full definition of environmental requirements for part selection.

V. FUTURE ACTIVITIES

The Cassini program would provide a timely focus for these measures. Certain rocket engines, including the Galileo 10-Newton thrusters, exhibit a boundary layer condition where the chamber fails to reach equilibrium, causing the Rocket Engine Assembly (REA) to significantly exceed normal temperatures. This is a concern for Cassini due to the mission requirement for long thruster burns. The Tayco RTD to be used on the Cassini REA combustion chamber "head end" is responsible for detecting high temperatures which could lead to premature REA degradation. Under a worst case scenario, the sensor could also detect a runaway condition so that one of the Marquardt R4-D engines could be shut down prior to catastrophic thrust chamber failure. This failure mode caused loss of an engine and damage to nearby equipment aboard a commercial satellite. Use of the Rosemount Model 118 RTDs is also planned for various locations aboard Cassini. JPL plans for Martin Marietta to conduct tests to affirm that:

1. The Tayco RTD installation will not be prone to failure, and

2. The insulating properties of the RTD wafer mount will not cause a lag in temperature readings.

In case the tests prove inconclusive, the JPL Flight Systems Section has expressed interest in obtaining more detailed information on the GSFC and U.S. Air Force anomalies listed in this report. Data on the TS models and in-flight environment would be useful to the Cassini design team.